

## تصميم تقاربى البرمجة للمحرك الإستنتاجى ذو عزم بدء الحركة العالى

### ITERATIVE PROGRAMMING DESIGN OF HIGH STARTING TORQUE INDUCTION MOTOR

BY

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المقدمة وصولاً إلى تصميم مدعم بالحاسب الآلى للمحرك الإستنتاجى ذو عزم بدء الحركة العالى ، والمرود بموصلات ذات شكل "رأسى" على العضو الدائر ، تم صياغة التصميم الكهرومغناطيسى بشكل "تقاربى البرمجة" . وقد تم بناء البرنامج ليؤدى الحدس المرحو بطريقة تبادلية تمكن المستخدم من اتخاذ قراره من بين الإختيارات المتعددة التى يقدمها الحاسب تأسباً على "نظام صير" المدعم به البرنامج . بالإضافة إلى تصميم المحركات الجديدة ذات القدرات المتوسطة والكبيرة ، يمكن إستخدام البرنامج فى إستبيان ومراجعة المحركات الموجودة فعلاً .  
و البرنامج يحقق المواصفات المطلوبة للألة بطريقة مرشحة من خلال عدد صغير من خطوات التقارب ، ويعطى النتائج فى هيئة "قائمة بمحركات التصميم" تحوى أيضاً الأداء المقدر كما يعطى خواص التفرد لعدد غير محدود من المتغيرات المختارة مع الأتزان .

#### ABSTRACT:

The electromagnetic design of high starting torque (HSTT) squirrel cage induction motors, fitted with wedge type rotor-bars is formulated as an iterative programming problem, to get a computer aided optimum design. The relevant CAD program is built to perform the proposed job in an interactive manner with both the user and the introduced Expert System. This enables the user to make his own decision when multiple choices are offered. The developed computer program can be used to design medium and large size new motors as well as to investigate or consult existing one. It yields very satisfactory results through a small number of iterations. The results are generated in form of a "Design Data Sheet" including all design data, and the expected no-load and rated performance. Also, the behaviour of a group of salient design and operational variables against slip can be plotted.

#### INTRODUCTION :

Away of the double-cage, the rotors of high starting torque squirrel cage induction motors are normally equipped with skin-effect conductors. They are characterized by their large depth having the smallest cross sectional area at the top of the slot. The wedge-type deep-bar belongs to these conductors. The HSTT squirrel cage induction motor, fitted with this type of rotor bars, is one of the most popular a.c. motors utilized in the different industrial applications. A proper design of such motor to satisfy the requested specifications depends mainly on a more precise

estimation of the rotor bar. A part of these specifications is the specific terminal values stated by the user. The other part is the standard specifications agreed by both the manufacturer and user. Among these specifications arise the ratios of starting torque and current to their rated values ( $T_R, C_R$ ) as the most important design variables. In order to approach the proposed values of both ratios, the rotor-bar dimensions must be properly chosen. Thereby, the required starting conditions and the whole motor performance can be ensured. Due to the large number of variables and inter-relations which must be handled through out the design process, the iterative programming manner is more suitable in formulating the proposed CAD program. In order to minimize the interactive manipulation carried out by the program user, the package is provided with an Expert System Routine.

#### EXPERT SYSTEM :

This system synthesises the previous theoretical, practical, and empirical knowledge gathered over long years in designing the HSTT induction motor. It is built in form of a handy routine. The required information can be easily obtained according to the factors characterising it. The expert system routine is helpful in determining [1-5] :

1. Proposed values of some factors such as : rated power factor, relative magnetising current, efficiency, and output coefficient.
2. Proposed values of some dimensional factors such as : the air-gap diameter, the air-gap length, and stator-slot-height.
3. Factors and variables related to the calculations of the magnetic circuit, the different specific permeances of leakage paths, and skin-effect.

The routine applies explicit relations and relevant interpolation methods through pre-stored lists. Also, it demonstrates visually the corresponding limits and information in cases of interactive multiple choice.

#### DESIGN PROCEDURE :

Generally, the design process of squirrel cage induction motor can be divided into the following major problems [8] :

- 1 - Design of magnetic circuit,
- 2 - Design of stator winding,
- 3 - Design of rotor cage,
- 4 - Determinations of equivalent circuit parameters, and
- 5 - Calculation and analysis of the expected behavior and performance.

These problems can be treated individually for motors with normal design. In case of HSTT induction motor this straight forward processing can not be applied. The reason is the complicated interrelations and dependence existing between many of the involved variables due to skin-effect in the rotor-bar during starting. This effect must be properly simulated by an adequate group of relations.

These relations relate the skin-effect variables to the dimensions of the rotor-bar and the required starting specifications.

The flow-chart given in figure (1) outlines the salient features of the suggested design process. For simplicity, most of the iterative and interactive operations do not appear in this chart. It follows now a brief account about a selected number of these operations.

### 1. Determination of Rotor-Bar Dimensions

In rotors equipped with skin-effect conductors, the bar current is forced at starting toward the upper portion of the bar resulting in an increase in the effective resistance and a smaller decrease in the effective leakage reactance of the bar [6]. As the speed grows, the rotor frequency decreases ( $F_2 = sF_1$ ). Accordingly, the effective bar resistance decreases to reach almost its dc value at rated slip. This temporary increase in the rotor resistance during the starting period, must be precisely determined in order to ensure the starting torque ratio and the desired torque/slip behaviour. Either the rotor bar-resistance or the slot specific permeance during starting can be related to their steady values under running conditions ( $s \cong 0$ ) by :

$$KR = r_{ac} / r_{dc} \quad \text{and} \quad KI = \lambda_{ac} / \lambda_{dc} \quad (1)$$

KR and KI are the resistance and inductance coefficient of the rotor-bar, respectively. In the design of wedge-bars, both coefficients can be expressed as functions of Beta, the ratio of the upper bar-width ( $b_0$ ) to the lower width ( $b_1$ ), and HBAR' :

$$KR = f(\text{HBAR}', \text{Beta}) \quad (2-1)$$

and

$$KI = f(\text{HBAR}', \text{Beta}) \quad (2-2)$$

HBAR' is an equivalent bar height; irrespective of the shape of the actual bar. It can be also expressed as function of the actual bar height, HBAR, and the slip  $s$  :

$$\text{HBAR}' = f(\text{HBAR}, s) \quad (3)$$

This relation yields at  $s = 1$ , the actual bar height :

$$\text{HBAR} = \text{HBAR}'_0 \quad (4)$$

Accordingly, the equivalent bar-height at starting,  $\text{HBAR}'_0$ , can be found with the help of relation (2-1) and the knowledge of the resistance coefficient at starting,  $KR_0$  :

$$KR_0 = f(KW, TR, CR, r_{bo}, r_{bi}) \quad (5)$$

KW is the rated output,  $r_{bo}$  and  $r_{bi}$  are the bar resistance outside and inside the iron core; respectively. They are function of the cross-sectional area of the rotor bar, ABAR, which is determined by the rotor copper sheet height ( $\text{HSH}_2$ ) and the rotor slot pitch ( $Y_{12}$ ) :

$$r_{bi} = f(\text{ABAR}) \quad \text{and} \quad r_{bo} = f(\text{ABAR}) \quad (6)$$

where  $ABAR = HSH_2 * Y_{12}$  ;  $HSH_2 = f(HSH_1)$  (7-1)

$$HSH_1 = f(AC_1, J, FF) \quad (7-2)$$

$AC_1$ ,  $J$ , and  $FF$  are the stator electric loading factor, current density, and filling factor, respectively.

It is evident from the relations (4) to (7), that the determination of the bar-height will follow an iterative interactive process between the parameters and specifications of the rotor and stator electric circuits. In each iteration step, the bar dimensions  $HBAR$ ,  $b_0$  and  $b_1$  will be calculated with help of  $ABAR$  and  $Beta$ . This process will go to end ; if :

$$b'_{0.5} \equiv b_{0.5} \quad (8)$$

where  $b'_{0.5} = b_0 + 5(b_1 - b_0) / HBAR$  (9-1)

and  $b_{0.5} = f(KW, CR, TR)$  (9-2)

The bar-width  $b_{0.5}$  is measured 5 mm below the upper edge of the bar. This width, determined by relation (9-1), must approach its value determined by (9-2); in order to satisfy the starting conditions.

## 2. Magnetic circuit calculations:

These calculations are essential to consult and recognize the no-load performance; especially the reactive component of no-load current; the magnetising current  $I_{\mu}$ . The relative value of this current to the expected rated current must be within 50% in case of large HSTT induction motors. This ratio is a guarantee that the required starting torque will be exerted. Thereby, the rated power factor could be in the range of 0.75 to 0.70. In addition to the no-load performance and rated power factor, the results of magnetic circuit calculations affect the specific no-load permeance, efficiency, and the stator-side thermal stresses. Therefore, a more precise calculation method had been chosen which considers for magnetic saturation[7].

The method applies an iterative process to get the ratio ALPHA. It is the ratio of the Maximum actual air gap fluxdensity (BGM) to the Average sinusoidal air-gap flux-density (DBG). Thereby, BGM can be determined where DBG is the already decided magnetic loading factor. With this maximum value, the magnetic circuit calculations can be started. According to the chosen magnetic material, the corresponding B-H curves and specific iron losses are to be included in the input data. All required empirical coefficients and experience are inserted in the Expert-System.

## 3 - Adjustment of the Diameter Current:

During the starting period the bar resistance and reactance are varying with slip:

$$r_b = f(KR) = f(HBAR, Beta, s) \quad (10-1)$$

$$\lambda_{s2} = f(KI) = f(HBAR, Beta, s) \quad (10-2)$$

In turn, the rotor parameters are also varying with slip during the same period. Accordingly, the rotor current will assume different loci between  $s = 1$  and  $s \approx 0$ . These loci are convergent and assume nearly the same circle as  $s$  approaches zero. To ensure the desired configuration of the torque and current behaviours against slip ; the diameter current at  $s=1$  must be properly estimated. Outgoing of the required starting specifications, the proposed value of this current can be to great extent exactly determined by :

$$I_d = f( KW, CR, TR, I_n ) \quad (11)$$

where in ,the proposed rated stator current,  $I_n = f( KW, V, PF, \eta )$  (12)

$V$ ,  $PF$ , and  $\eta$  are the rated voltage, power factor, and efficiency, respectively. In the other hand a preliminary value of the diameter current can also be determined at this level of the design process :

$$I_{dd} = V / X_1 = V / ( X_1 + X'_{20} ) \quad (13)$$

where  $X_1$  is the total motor reactance at  $s=1$  referred to the stator. The preliminary current  $I_{dd}$  is that reactive current expected to be consumed at  $s = 1$ . It is a measure of a satisfactory performance at both starting and rated conditions, and must be nearly equal to the proposed value  $I_d$ . This can preferably be done by modifying the standstill rotor reactance  $X'_{20}$ . The major part of  $X'_{20}$  depends mainly on the specific permeance of the rotor slot, and in turn on the rotor slot dimensions :

$$X'_{20} = f( \lambda_{s20} ) \quad (14)$$

Any unacceptable deviation in the preliminary value  $I_{dd}$  can be avoided by a relevant modification in the rotor tooth-height or the ratio  $\beta$ . Thereby the rotor slot specific permeance  $\lambda_{s20}$  can be adapted to get  $I_{dd} \approx I_d$ .

#### APPLICATIONS, USAGE, AND RESULTS :

The predicted CAD program can be used to design medium and large size new HSTT induction motors. It can also be used to investigate already built motors when it is required to rewind, test, or consult them. The input data are minimised to be the required terminal specifications, and the specific data of the chosen materials.

The user will find the output data in two files. The first file contains the design results in form of a "design data sheet". This sheet includes all detailed information about : (1) Dimensions of stator and rotor laminations; including slot dimensions. (2) Stator winding, rotor cage, magnetic circuit, and (3) Expected no-load and rated performance. In addition, the terminal specifications and the design data recommended by the Expert System are also included. The second file can be handled by plotting routines to get the characterising behaviour of a group of operational variables against slip.

The program had been tested through the redesigning of a group of already built deep-bar induction motors. Figures ( 2 ) to ( 7 ) summarizes the behaviour and performance of 500 KW, 3000 V, 60 HZ, 125 r.p.m motor, which is already built for :  $CR = 3.5$ ,  $TR = 0.5$ , and  $\beta = 0.5$ . Also designs of this motor having the same

terminal specifications; but different Beta, different starting torque and current ratios are carried out. The figures reveal that all designs hold to a great extent the same expected no-load and rated performance. Although of this result, the torque behaviours are not the same. This emphasizes the fact that CR, TR, and Beta must be chosen to interact in a perfect harmony to get the required behaviour; a job which can be easily done by the program.

#### CONCLUSION :

A quick and simple CAD program has been developed to design HSTT squirrel cage induction motors fitted with wedge-type rotor-bars. The program performs the design process in an iterative interactive manner to approach the proposed objects stressed by the required specifications. The package includes an Expert System Routine which simulates whole of the theoretical and empirical information, practical feelings and limits guiding the design procedure. In addition to the design of different size new motors, the program can be used to investigate or consult existing one. The results reveal good satisfaction through a small number of iterations. The author suggests the program as an elementary step in starting a national industry of HSTT squirrel cage induction motors.

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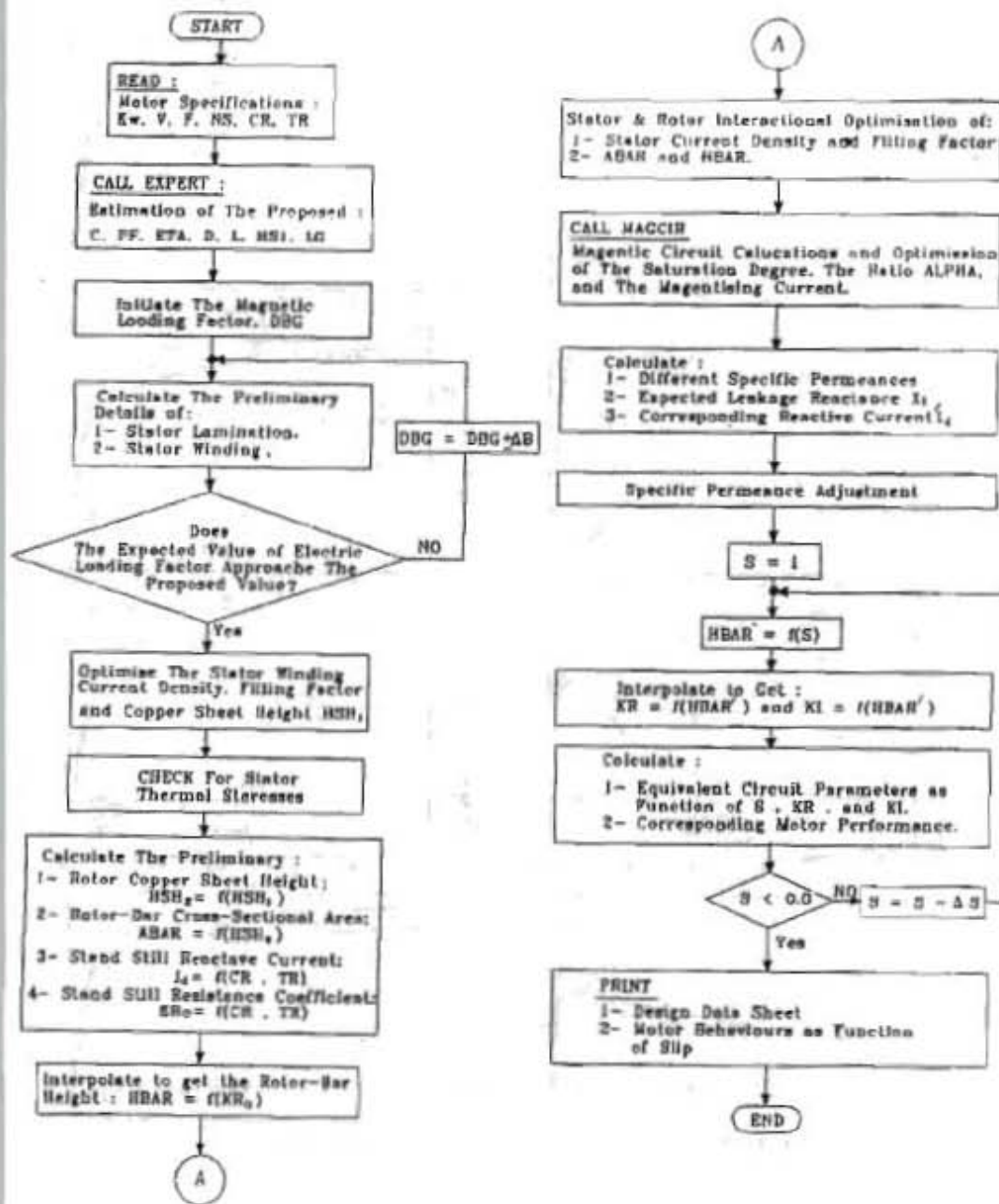


Fig.(1) : Computer Programming Flow Chart.

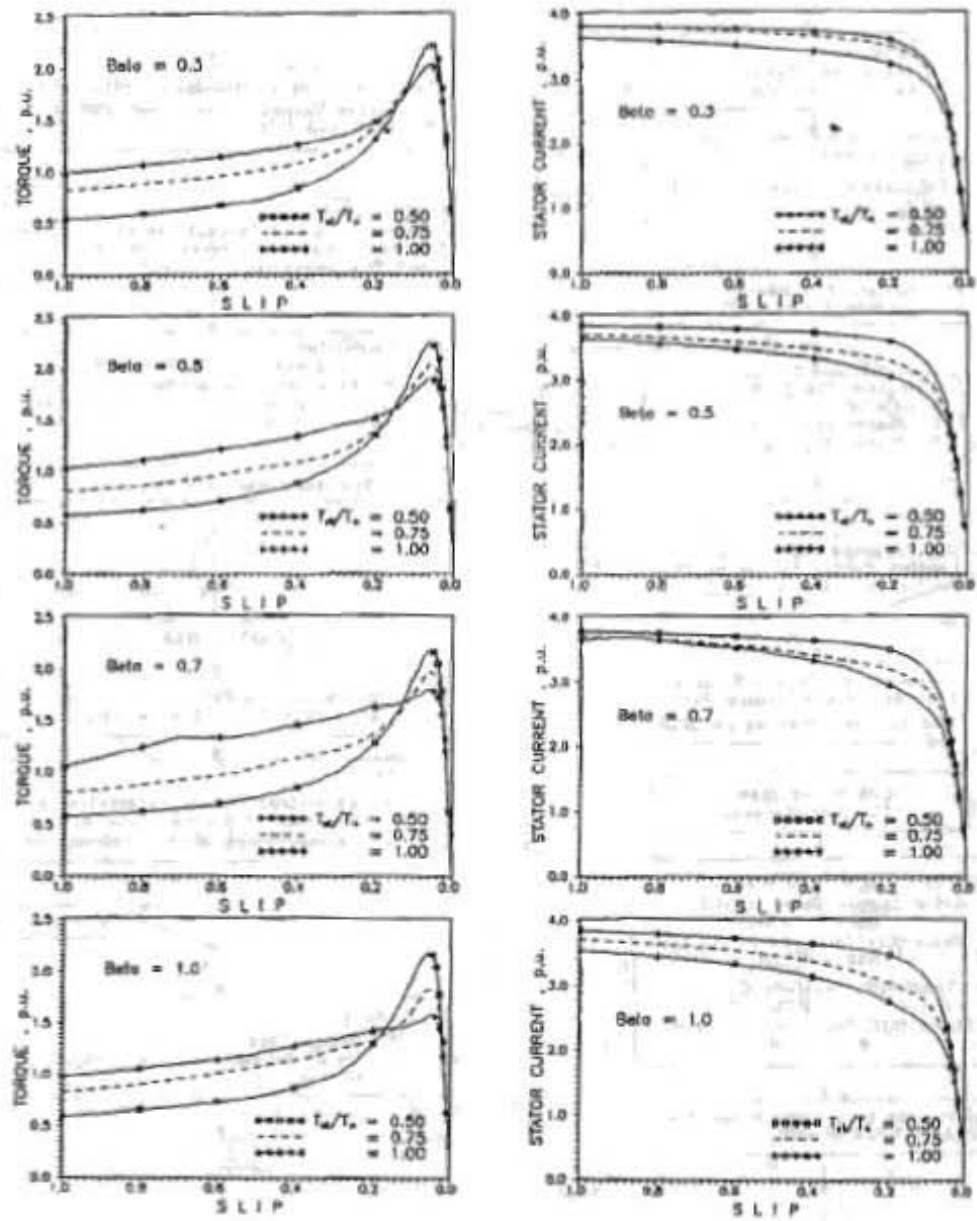


Fig.(2) : Holding the requested starting torque and starting current ratios for given BETA.



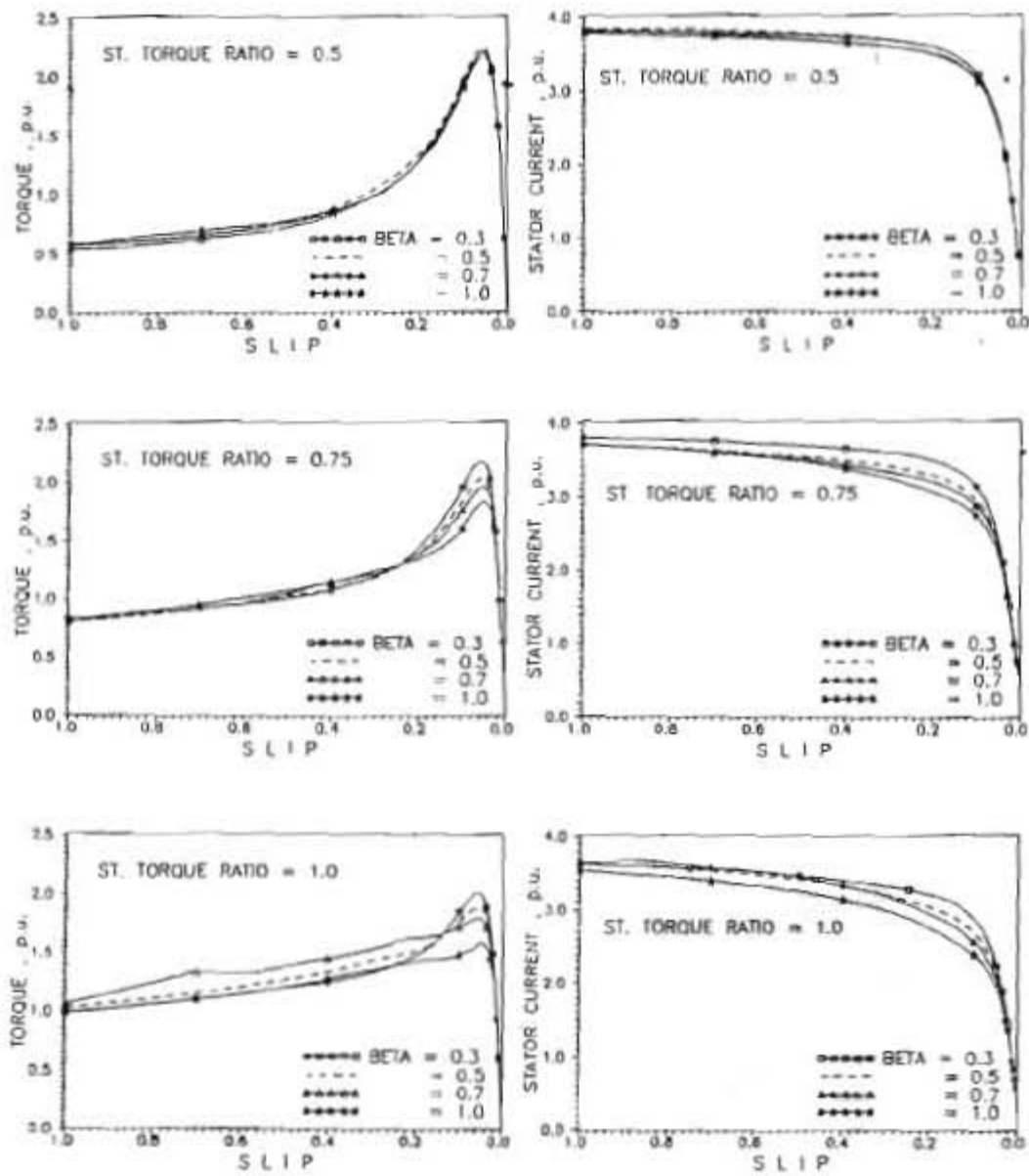


Fig.(3) : Effect of BETA on the requested starting torque and the starting current ratios, as well as the maximum torque.

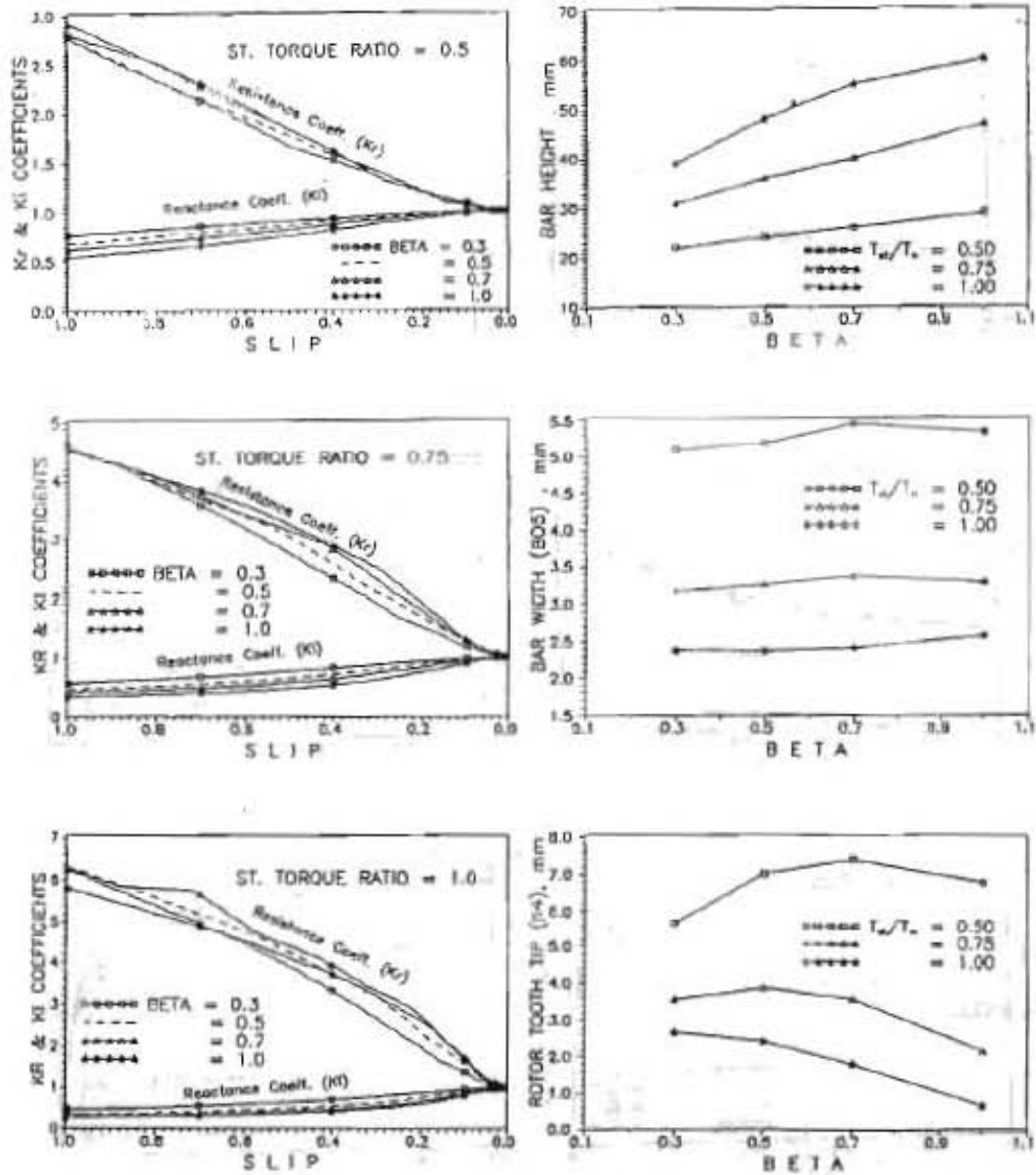


Fig. (4): Variation of the rotor-bar resistance and reactance coefficients against slip.

Fig. (5): Pertaining the rotor-bar design.

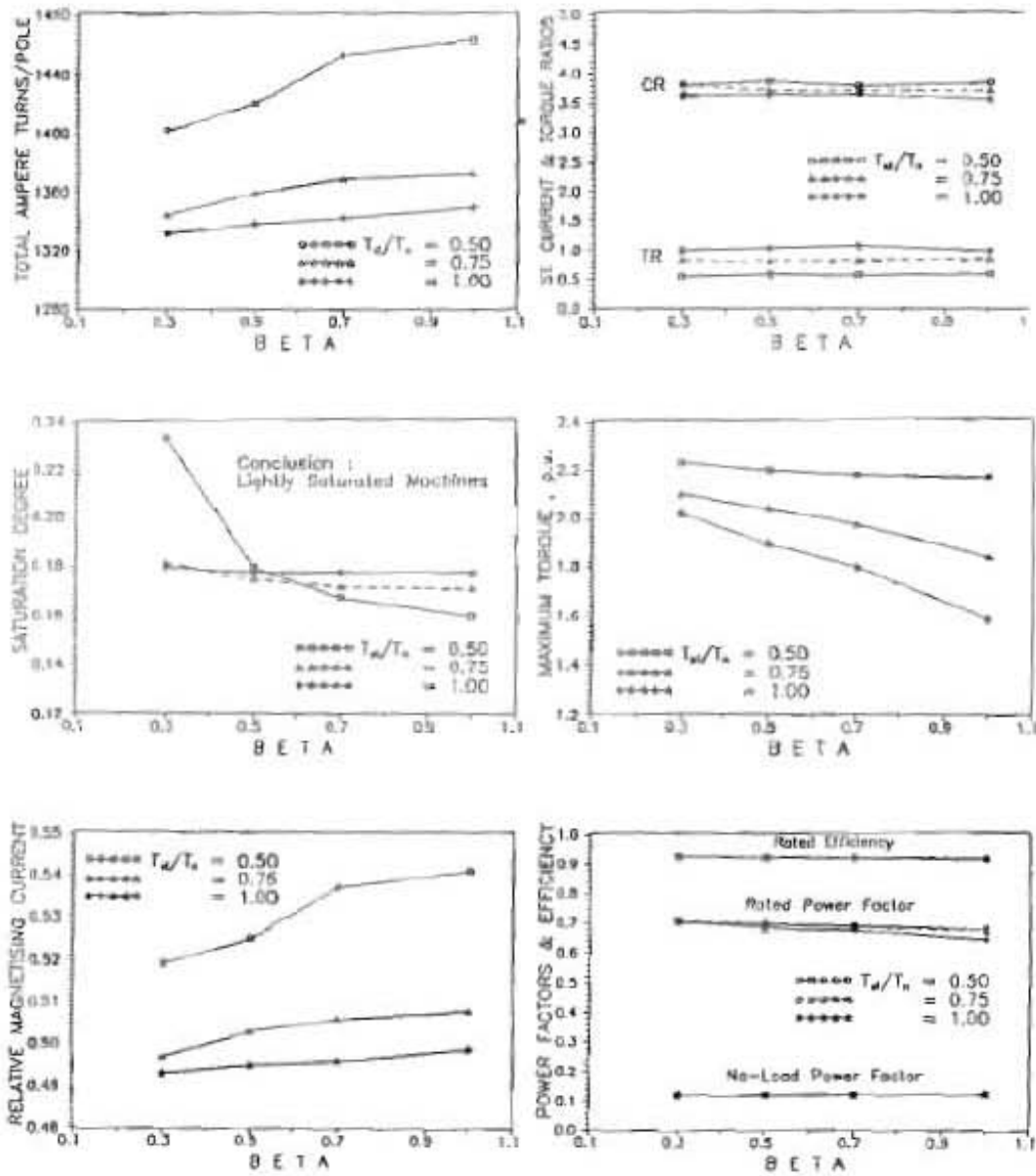


Fig.(6): Pertaining the magnetic circuit calculations.

Fig.(7): Pertaining the expected performance.